THE IMPACT OF V/STOL AIRCRAFT ON INSTRUMENT WEATHER OPERATIONS

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Presented at the AGARD Flight Mechanics Panel Meeting
on "All-Weather Operation"

Munich, Germany
October 12-14, 1964

NATIONAL AERONAUTICS AND SPACE ADMINISTRATION

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INTRODUCTION

Everyone is familiar with the potential of V/STOL aircraft to operate from small, unprepared fields. In addition, V/STOL aircraft have the potential for safely approaching the ideal of "zero-zero" weather operation. However, the impact of V/STOL aircraft on instrument weather operations, in general, will not be appreciable in the next 10 years because of the extensive research and development needed in pilot displays, instrument approach techniques, and aircraft handling characteristics in order to make low-speed, precision instrument approaches practical. Once these problems are solved, however, it would seem possible to operate with greatly reduced weather minima and, with advanced planning, to accommodate V/STOL and CTOL (conventional take-off and landing) aircraft traffic simultaneously in a terminal area, resulting in increased airspace utilization and airport capacity.

BENEFITS OF NEAR "ZERO-ZERO" CAPABILITY

The benefits to commercial operations from operation in lower weather minima will come from a reduction of diversions and missed approaches, and a reduction in cancellations due to existing or forecast minimum weather conditions, as well as a reduction in traffic delays by making better use of airspace in high-density terminal areas, particularly. The uneconomically high cost now predicted for electronic equipment to reduce minimas below 100 feet and 1/4-mile visibility for the present jet transports predicted in references 1 and 2 may not hold true for the much slower V/STOL landings because the pilot will have more time.

Parallel advantages will be realized for military operations. Strike fighter sorties or low-level reconnaissance, as well as troop movements, under weather conditions that now severely hamper military air operations for a typical northern European winter, for example, would provide a terrific military advantage of surprise and movement. I am thinking of the capability of safe and practical visual flight operations under low ceilings and low visibilities through use of reduced speeds as well as the capability of instrument operation down to the treetops for return to home base when necessary.

STATE OF THE ART IN V/STOL INSTRUMENT OPERATION

It is safe to say that no "high-performance" instrument flight (slow speed and steep gradient to a specific landing spot) has yet been conducted with V/STOL aircraft other than helicopters. As a matter of fact, after more than 20 years, "high-performance" instrument flight with helicopters is not now being done operationally. The first-generation test-bed V/STOL aircraft flown in the United States have been totally unsuitable for instrument approach investigation although several have been studied with the instrument approach in mind. At the moment, the automatic approach for general V/STOL application has not been developed and seems a very long way off, so will not be discussed, except to say that it will have to be compatible with, and developed concurrently with, a suitable guidance system which is also, at present, nonexistent. The pilot's job, as a necessary part of the control loop for the immediate future will not be simple, even with stability and control augmentation, and he will need improved displays. The current displays available for service use are interim steps and do not give the pilot the immediate impressions of his real world situation necessary to do the job as expeditiously as he does visually.

It was learned in studies at Langley, several years ago, that maneuvers such as the landing approach which are performed easily in helicopters visually are an order of magnitude more difficult under instrument flight conditions with state-of-the-art pilot displays, particularly when following a precision guidance system to a specific landing spot. These helicopter studies (see refs. 3 and 4) illustrate problems of piloted instrument flight which are functions of speed and other factors common to all V/STOL aircraft. It has not been found possible to make vertical approaches on instruments, so far, even with suitable guidance systems (see ref. 5). Limitations on the minimum speed suitable for flight in combination with limiting rates of descent determine usable flight-path angles for approach. For instance, the angular deviations in flight path in a given time for a given upset are inversely proportional to speed, and normal acceleration cues as a warning or as a guide for the pilot are noticeably lacking at low speed. Also, wind effects on rate of approach to touchdown, rate of descent, and heading offset to counteract drift, and the wind gradient effects in descent on drift and glide-path corrections become large at low speed. In fact, the effects of wind gradients and gusts on glide-path control become increasingly more pronounced as the glide path is steepened. At the low speeds suitable for glide-path angles of 6° or over lift or thrust throttle changes, or angular vectoring of a lift-thrust system will be the primary glide-path control. In all other respects normal piloting techniques have been found best down to the lowest practical speeds, in our experience; i.e., the aircraft is flown laterally level with a heading offset for drift correction, and is turned for lateral offset correction by banking, keeping sideslip zero. Maximum rates of descent found suitable for low approaches have been 500 to 700 feet per minute. Figure 1 shows the relationship of speed to glide-path angle at these descent rates.

As in all instrument flight, considering presently available pilot flight instrumentation, the pilot must essentially execute one task at a time. For the instrument approach, therefore, he must keep the number of variables at a minimum so he can concentrate, insofar as possible, on flying the precision approach path. This means flying a straight path and maintaining an essentially constant speed and configuration until breakout.

As approach paths were steepened in our helicopter investigations it was found that increased anticipation was required in acquiring the glide path to prevent overshooting and difficult corrections later. It was found that about 90 seconds, or $1\frac{1}{2}$ minutes, are necessary on the descent path in order to become adequately established on it, considering that marked wind gradient effects at low speeds are commonly encountered in moderate winds at heights of about 200 feet, and in strong winds up to heights of 500 to 700 feet.

It is generally agreed that at the lower speeds possible with V/STOL aircraft stability and/or control augmentation will be required for operational "high-performance" instrument approaches even though it is believed that the aircraft can, with adequate design, be flown by the pilot with no augmentation in visual flight conditions. The augmentation may be in the form of angular velocity damping or attitude stabilization. At any rate, adverse yaw or sideslip in turning maneuvers should be kept to a low value. Recently, two large STOL airplanes, one a jet with a blown flap and the other a propeller-driven type, have used control interconnection very successfully to reduce yaw due to use of roll control. It has been found from Ames Research Center tests (ref. 7) that the use of the derivative $\dot{\beta}$ in stabilization systems can successfully limit and damp sideslip excursions, preferably if used in combination with control interconnection. The large jet STOL aircraft mentioned above uses this derivative with considerable success. At lower speeds than these STOL aircraft are capable of, however, the need for additional augmentation inputs can be expected. Figure 2 shows variable stability helicopter results from reference 6 which indicate directional characteristics desirable for easy and precise course corrections for a precision approach at 45 knots. The optimum line indicated corresponds to critical damping of the "Dutch roll."

A first look at the U.S. V/STOL test-bed aircraft indicates several characteristics of importance to the instrument approach. For those types with a fixed wing having no stall protection, such as the jet, tilt-duct, etc., control of angle of attack will be required except at very low speeds. Such aircraft tend toward inadvertent and accelerated settling at low speed if lift thrust or power is not correctly adjusted, thus aggravating angle-of-attack control. Also, at constant speed, the control of rate of descent by lift thrust or power changes alone to stay on the glide path represents a changing angle of attack which must be within certain acceptable limits. If angle of attack must be controlled within moderate limits, approximate drag balance on steep glide paths must be obtained by vectoring the lift-thrust system (see ref. 8).

INSTRUMENT APPROACH FOR THE FIRST-GENERATION V/STOL AIRCRAFT

Factors Establishing the Pattern

The factors which determine the instrument approach pattern are: (1) Conditions at the landing site such as the weather minima capability desired, the size and preparation of the landing area, and the surrounding terrain features; and (2) the limitations of the aircraft, and the pilot (considering his instrument displays) in negotiating a "high-performance" flight path. In accord with the previous discussion of the present state of experience and development in V/STOL instrument flight it is assumed that essentially a constant speed and constant glide angle will be maintained until visual contact is made by the pilot with the landing spot in the case of VTOL operation, or the approach end of the runway, in the case of an STOL operation. The use of approach lighting systems is not considered herein.

The visibility required to perform visual VTOL and STOL landings from 3° or 6° glide slopes is shown in figure 3. Figure 4 shows the ceiling required for VTOL and STOL landings from 3° and 6° paths. The plots were derived by assuming that time required by the pilot for the final landing maneuver after becoming visual can be analyzed as follows (see ref. 9):

(1) 2 to 3 seconds for recognition of the situation and decision

(2) 2 seconds for developing cues for the initiation of flare or deceleration

(3) 1 to 2 seconds to initiate aircraft response.

Thus a total of about 6 seconds is required from breakout until initiation of flare or deceleration. The average operational VTOL deceleration is considered to be 0.15g. The analysis does not specifically consider any but minor changes in alinement of the flight path after breakout.

The plots show clearly that the visibility and ceiling required are functions of the aircraft speed. The speed that is important here is actually ground speed. Also, for any given speed, a VTOL landing requires more visibility and ceiling than does an STOL landing because the VTOL must decelerate to zero speed within the visibility existing, whereas the STOL can lose this speed on a runway. It is assumed throughout that the VTOL can land as an STOL when the situation dictates. Furthermore, the ceiling required is almost directly proportional to angle of approach, so, for minimum ceiling operation, it is best to operate at 3° if otherwise feasible. If not, a reduction in speed is necessary.

Should the aircraft not be alined with the intended track when breaking out, a "sidestep" maneuver is, of course, required. The distance required for such a maneuver at constant bank angle is a direct function of speed as shown in figure 5, the time remaining constant. However, time can be traded for distance at the desire of the pilot. Such a maneuver could, if large enough, add to the time and distance required before flare in STOL operation, but would probably not add time or distance in the VTOL case because of the additional time available while the VTOL is decelerating to zero speed.

The Pattern

On the basis of past experience in attempting to fly "high-performance" profiles, a 6° glide path is chosen to a VTOL landing area 500 feet square and is the basis for establishing the illustrative pattern in figure 6. The 6° slope provides good terrain clearance and shortens the final approach to about half that for a 3° slope. The 6° slope also allows a fair range of approach speeds without exceeding a rate of descent of 700 fpm. I have assumed in the figure a final approach speed of about 45 knots as this gives a VTOL landing capability with about a 100-foot ceiling and 1/4-mile visibility. Also, 45 knots is probably the minimum practical speed for the near future from the standpoint of handling qualities and the effects of average winds.

I would like now to discuss the approach pattern as the aircraft flies it. It is assumed that some type of navigational fix is provided to establish the entrance to the landing pattern. The aircraft will be slowed while approaching the fix so as to pass the fix at minimum airplane speed. Lift engines may well have to be started prior to reaching the fix. The aircraft is turned to a downwind heading and a partial conversion is made so as to go through the conversion stages where large longitudinal trim changes, strong ballooning tendencies, or large power changes may occur before precision navigation is necessary. A speed as near final approach speed as possible is established which will allow adequate maneuvering. This might be about 75 to 90 knots. The downwind leg otherwise need be only long enough to allow adequate time for establishing the inbound alinement before intercepting the glide path, or perhaps $1\frac{1}{4}$ minutes.

The patterns turns are all made at about a 10° bank angle. The crosswind leg is about 1/2 minute long, primarily to allow for unknown wind effects.

As the turn is made into the final approach course, bracketing is begun and the speed is reduced almost to that for final descent. Establishing alinement has been found to require about 1 minute. At about 45 to 50 knots, then, the final glide path of 6° is entered from about 1000 feet with configuration adjustment as required. Some anticipation of the glide slope is required as there is a tendency to overshoot the steeper slope and to start the descent high on the glide path. The final descent will require about $1\frac{1}{2}$ minutes to stabilize, so the 1000-foot intercept will provide enough time for descent rates up to 700 fpm.

After breakout from the instrument conditions and the landing area is sighted, final conversion and deceleration to hovering is made. At the average 0.15g deceleration assumed, the hover will be reached in about 22 seconds. The landing should then not require more than 10 or so seconds. The time after breakout to landing is thus assumed to be about 1/2 minute.

A comparison of the pattern size of a V/STOL operated in this manner with a conventional aircraft pattern is shown and it is approximately half the size of the airplane pattern because of the reduced speed and the steeper glide path assumed.

Adding up the slow speed segments of the V/STOL pattern illustrated, one finds that about 5 minutes have been spent at low speeds. For jet-type V/STOL this means that for 5 minutes the thrust may be as high as 80 to 90 percent of the hovering thrust. This is, indeed, hard on fuel consumption and could very well mean a prohibitive reduction in radius of action or payload as a V/STOL. For such a case the only alternative known at present seems to be to revert to operation as a normal airplane for the instrument approach prior to breakout. Ceiling and visibility minima would be correspondingly increased.

It is of interest to note that in a visual approach, given the aircraft handling qualities specified in AGARD Report No. 408 (ref. 10) with respect to longitudinal trim and control, the pilot can probably decelerate from 150 knots to a vertical landing in about 1 to $1\frac{1}{2}$ minutes, even along moderately curved flight paths to suit the situation and the pilot's own judgment. Thus, he can save at least $3\frac{1}{2}$ to 4 minutes of high-power operation over the instrument approach described. To achieve this saving in an instrument pattern the pilot must be able to obtain and integrate the same information in a given time from instrument displays as he does naturally from the real world during a visual approach. Although this is not possible with present displays, the saving of a large part of this $3\frac{1}{2}$ to 4 minutes difference in high-power operation sets a goal for V/STOL instrument flight development.

In addition to shortening the time in low-speed flight, further fuel savings may well be made by the choice of optimum control powers about the three body axes, and optimum stability and control augmentation. Should control power be too low, for instance, the bleed flow demands or control applications may be required for excessive lengths of time to accomplish corrections, thus using excess power and fuel. Also, if the augmentation is adequate, corrective control inputs by the augmentation system can correct deviations sooner than the human pilot could, thus demanding less power and fuel. Little useful data along these lines have yet been obtained.

Air Traffic Control With V/STOL

A question immediately raised by commercial operators when use of low speeds for patterns and landing is discussed is: "How do we use it with CTOL aircraft? ATC is even now asking some aircraft to use higher speeds on the approach to speed the orderly flow of traffic." It is obvious that the V/STOL aircraft cannot be used as such in the same approach and landing lanes as the CTOL and survive. However, with long-range ATC and airport planning in the commercial case it would seem that, for short haul and feeder-line service to the large terminal airports, separate landing areas and approach guidance systems could be provided which would permit the independent operation of V/STOL at CTOL airports. Figure 7 illustrates a possible airport design with mixed traffic in mind.

A way of handling the V/STOL traffic, when mixed with CTOL, might be to arrange the approach lanes at nearly right angle to the approach lanes for CTOL and assign them to lower altitude levels from, say, 1500 to 3500 feet. Since the high-performance CTOL aircraft of modern fleets are operating at higher altitudes, have pressurization, and are capable of steep descent paths, it should not be a great handicap to have them descend to their own final approach paths after passing over the V/STOL levels. The V/STOL holding patterns could be at high altitudes, but not closer than 30 to 50 miles, for instance, from the airport so that descent could be made at some distance from the airport into the low-level approach lanes to the V/STOL instrument approach facilities without interference with the higher altitude CTOL flow. Figure 8, from reference 11, is an illustration of this idea as applied to Kennedy Airport.

The V/STOL can slow down to well-regulated slow maneuvering and approach speeds to keep the approach pattern small, as was illustrated in figure 6. For this reason it would also be desirable to use at least a 6° final descent path. The letdown facilities for V/STOL should be omnidirectional to allow final approaches as close into the wind as possible, but also to insure that there is no conflict with CTOL traffic because of direction of landing. Perhaps an omni-glide path capability would also be desirable.

For the separation of slower V/STOL aircraft from each other and for separation from the CTOL also, it would seem reasonable to reduce separation to 1 mile instead of the present 3 miles. For example, at 50 knots, if on a collision course with another aircraft, a 3-second delay for decision plus the radius of turn executed would be little more than 1/8 mile, whereas at 180 knots, this distance is nearly $1\frac{1}{4}$ miles. Thus, 1-mile separation would seem to provide more than adequate safety at speeds of the order of 50 knots. This 1 mile would represent about 1-minute separation on final. This time separation is not thought to be a problem from the vortex wake standpoint because:

(1) the downward drift of the vortex trail would be at a higher rate than CTOL aircraft because of the higher lift coefficients involved; and

(2) the vortex wake would tend to deteriorate in strength more rapidly because of the vorticity along the span due to the lifting systems of the V/STOL (see ref. 12).

Of course, it is important that all aircraft follow the same glide path to insure that following aircraft will definitely be above the preceding vortex trail.

Assuming that it is feasible to land V/STOL and CTOL aircraft simultaneously on approximately parallel paths with no more than a mile separation, the capacity of the airport should be at least doubled. For instance, with 1-minute separation the V/STOL could land 60 per hour, whereas the conventional traffic with $1\frac{1}{2}$ minutes separation could land 40 per hour for a total of 100 aircraft per hour. This, of course, is assuming only one landing pad, strip, and aid for each type of aircraft. The increased capacity potential of the airport should, indeed, be of interest to commercial operators for economic reasons, eventually.

The power required during the landing approach for V/STOL, other than helicopters, will be high and the noise produced higher than conventional types. Figure 9, from reference 11, compares noise level on the basis of distance from touchdown for propeller-driven types, the V/STOL on a 6° path and the conventional on a 3^{o} path. The V/STOL is the noisier, but if landing on a pad some distance inside the airport boundaries, the noise level at the boundary may be less. Figure 10, from reference 11, compares jet-type V/STOL and conventional aircraft with respect to noise, again on a 6^{o} slope for the V/STOL and 3^{o} slope for the conventional. In this case, the V/STOL is less noisy than the conventional jet, primarily because of the steeper flight path.

This discussion has again assumed operation for several minutes at high power settings in slow flight. Should improved pilot displays or approach techniques be developed that would reduce the time in slow flight, the patterns illustrated would certainly change. The manner in which they would change cannot be forecast at the present, but it is hoped that the higher maneuvering speeds prior to initiation of the deceleration to landing will not expand the overall pattern required.

SUGGESTED RESEARCH AND DEVELOPMENT PROGRAMS

It has been indicated that one of the important capabilities of V/STOL aircraft, the ability to reduce the instrument weather minima for safe operations, can be realized in a reasonable time frame only if considerable effort is begun now to support research and development effort in at least three areas. These are:

First: The handling qualities in terms of control power and the degree of stability augmentation and/or control interconnection arrangements must be worked out so that the piloting workload at V/STOL speeds becomes equivalent to present CTOL transports.

Second: Extensive research and development of pilot displays is needed for the V/STOL's capabilities of making slow and steep approaches. If the pilot had a display which enabled him to assess his situation in the real world as readily as he does in a visual approach, he could do his transition during his approach in such a manner as to save several minutes of high-power operation. The flight director can make a given task considerably easier, but does not give the pilot the knowledge of his situation necessary for him to use his own good judgment in selecting or adjusting the trajectory of his aircraft. Considerable progress has been made in recent years in the form of contact analog representations of the real world although they are still bulky and complex. However, insufficient information is presented in present ones without additional instruments to adequately judge height and flight-path angle, and the distance to and rate of closure on a landing spot. Also, the angular field is inadequate for landing pattern maneuvering. The three-dimensional effectiveness is lacking, in other words.

Third: An active program of specific flight research should be undertaken with the first generation of near-operational V/STOL airplanes. This specific research should be directed toward development of practical precision instrument approach techniques with the saving of time and fuel in mind, and toward development of stability augmentation and pilot display requirements. The aircraft types available with the kind of investigation for which each can be of value are:

(1) The Hawker P.1127 with which to study the use of thrust vectoring on conversion techniques and glide-path control.

(2) The Mirage III V with which to study the use of attitude and lift engine throttles on conversion techniques and glide-path control.

(3) The VJ-101C, assuming the capability for variations in control power in roll and in the mode and degree of stability augmentation, with which to study control-moment requirements and fuel used for control with the various combinations.

(4) The Dornier DO-31, which is of larger size, can carry two pilots, and has a combination jet lift system, with which to conduct more extensive and realistic instrument flight studies of a fixed-wing transport.

(5) The XC-142 which is comparable in size to the Dornier DO-31 but is of the propeller-driven, tilt-wing type, with which to provide comparable information for this type.

This cross section of aircraft types is quite comprehensive. It encompasses three fixed-wing planforms and five lift-thrust arrangments so that a broad spectrum of problems associated with stalling, flight-path control, conversion, and longitudinal and lateral stability and control should be available for study. The techniques for slow and steep approaches by instrument may be quite different for fixed-wing types where the wing must be kept below stall incidence as compared to the tilt-wing type in which incidence is very high and stalling is a function of power. It is realized that single-place aircraft such as the fighters are not the best suited for instrument flight studies, but it is felt that considerable can be learned by using chase airplane techniques and having a specific objective to explore realistic instrument flight techniques.

CONCLUSIONS

One of the real benefits to be gained by the use of V/STOL aircraft is the reduction of weather minima for safe, operational use.

In order to make this possibility a reality in the next 10 to 15 years, it is necessary to expedite work now along these lines:

(1) Improve the aircraft handling qualities as required to make the pilot workload comparable with present CTOL aircraft.

(2) Develop vastly improved pilot displays.

(3) Conduct flight research, specifically to explore practical precision instrument approach techniques, considering the known capabilities of guidance systems.

An excellent opportunity exists for getting information along all three of these lines by doing objective flight research with the generation of V/STOL aircraft now approaching flight status in Europe and USA.

In order to use V/STOL aircraft in high-traffic-density terminal areas effectively, a new approach to the ATC system is advisable and arrangements should be provided for separate approach and landing facilities for V/STOL aircraft where the same airports are used as for CTOL aircraft.

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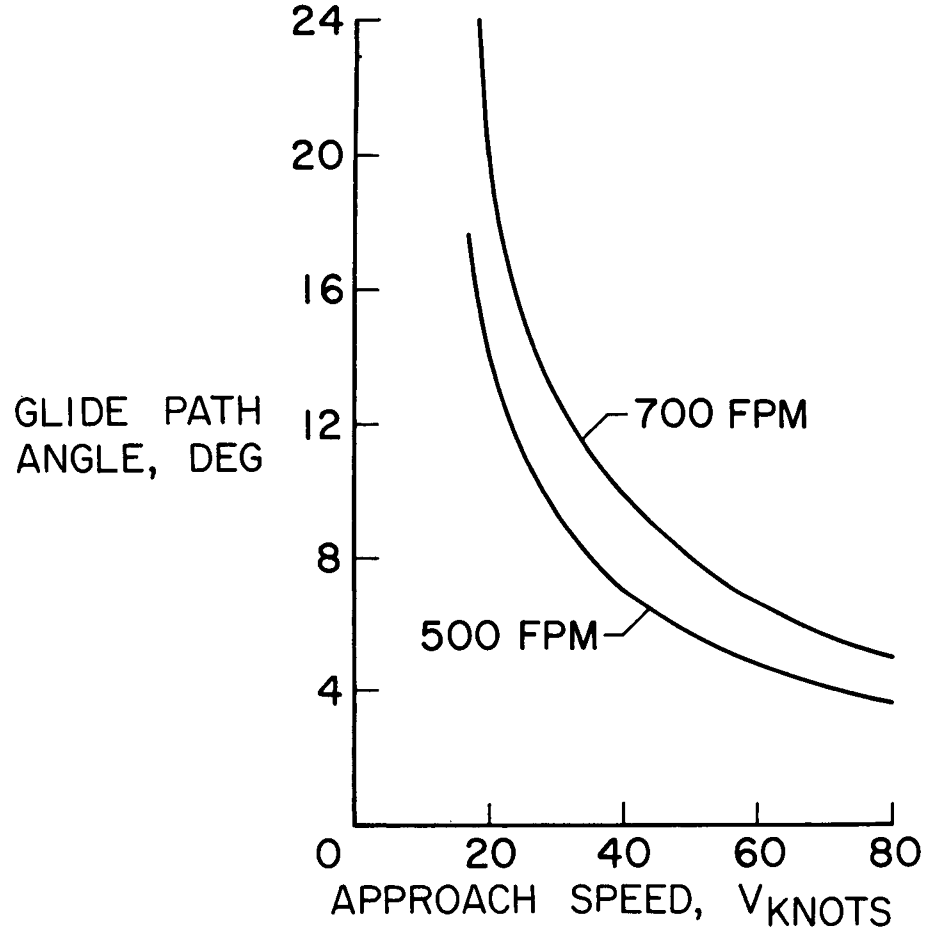

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Figure 1.- Glide path angle as a function of speed for desirable and limiting rates of descent.

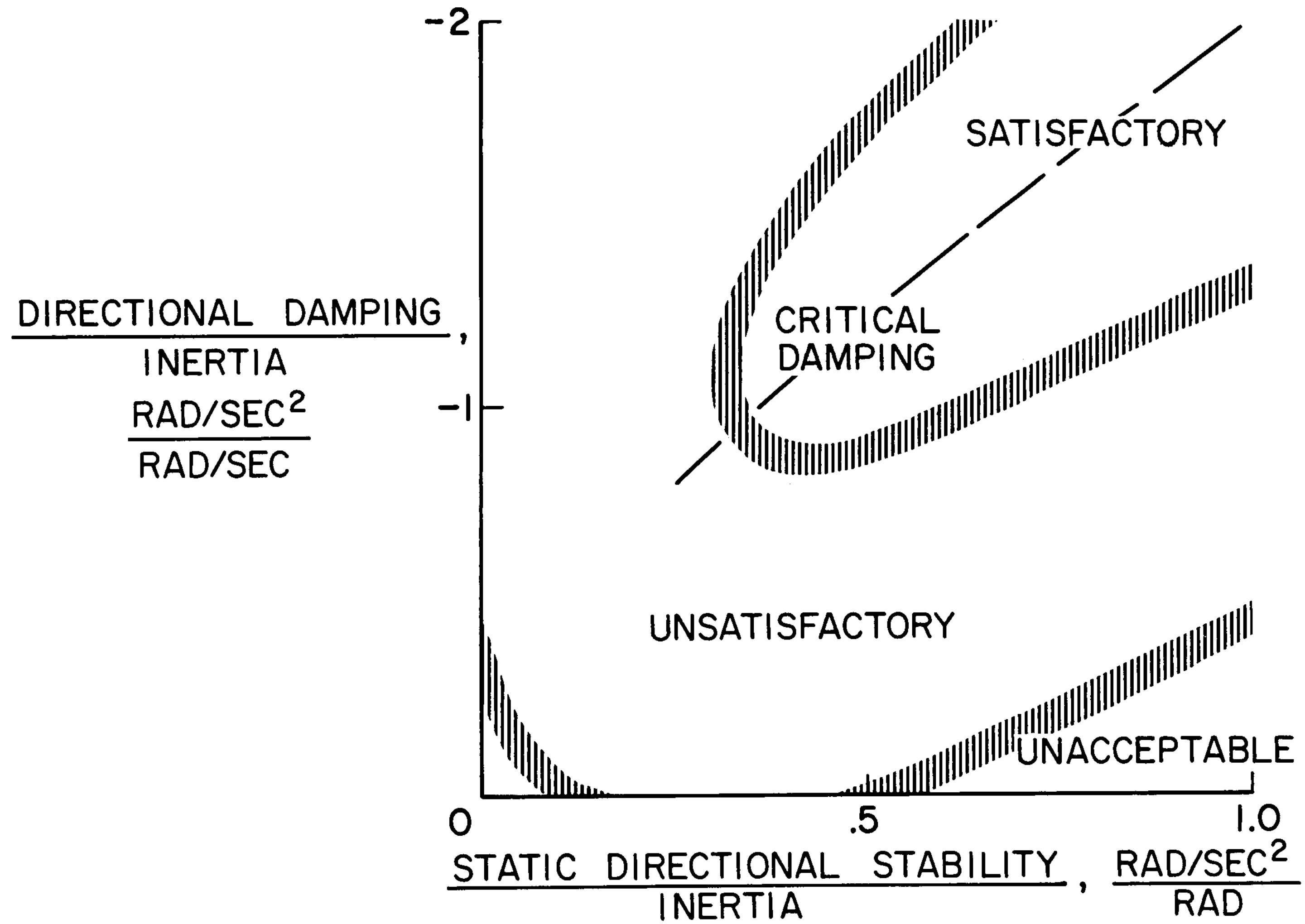

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Figure 2.- Static directional stability versus damping found satisfactory for ILS approach at 45 knots.

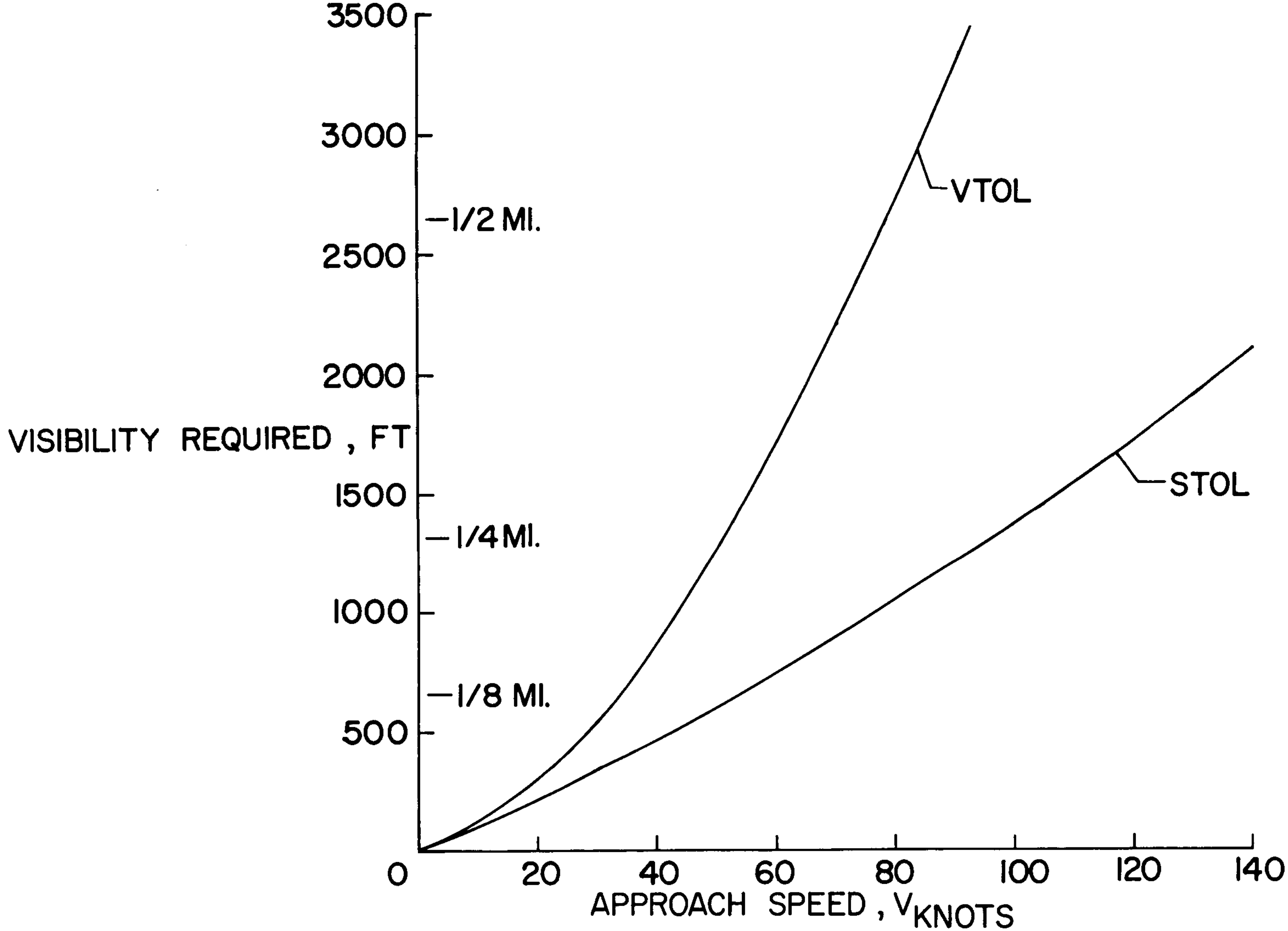

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Figure 3.- Slant range visibility required for VTOL and STOL operations.

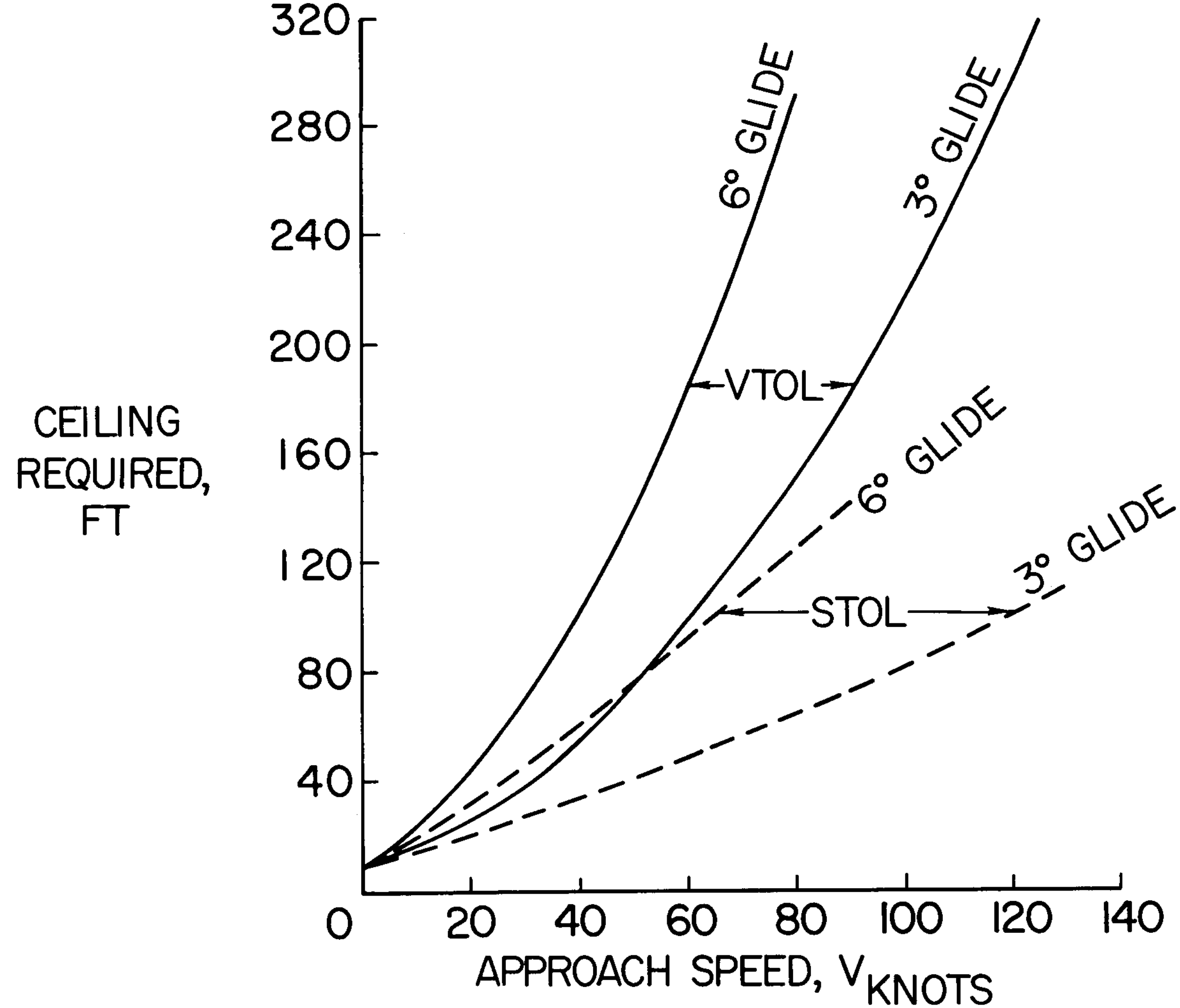

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Figure 4.- Ceiling required for VTOL and STOL approaches for two glide angles.

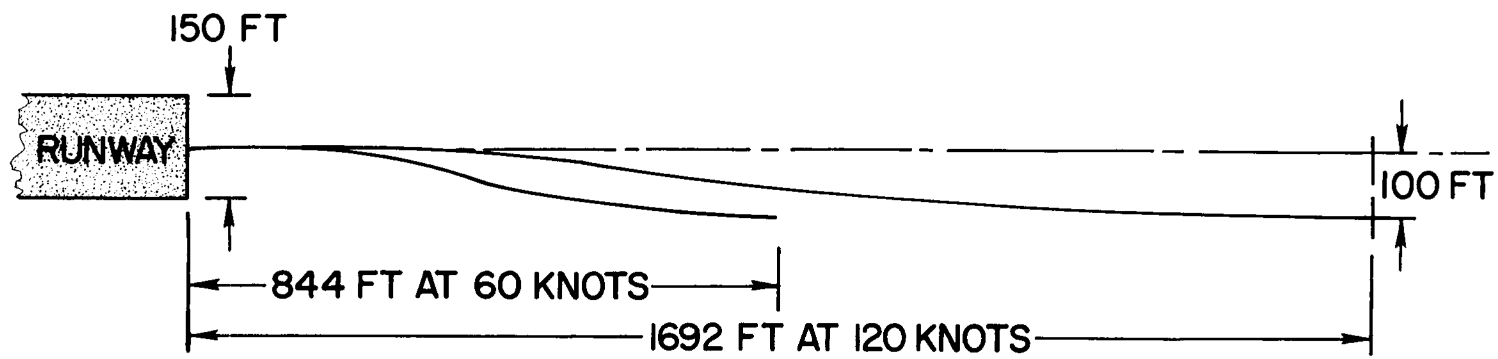

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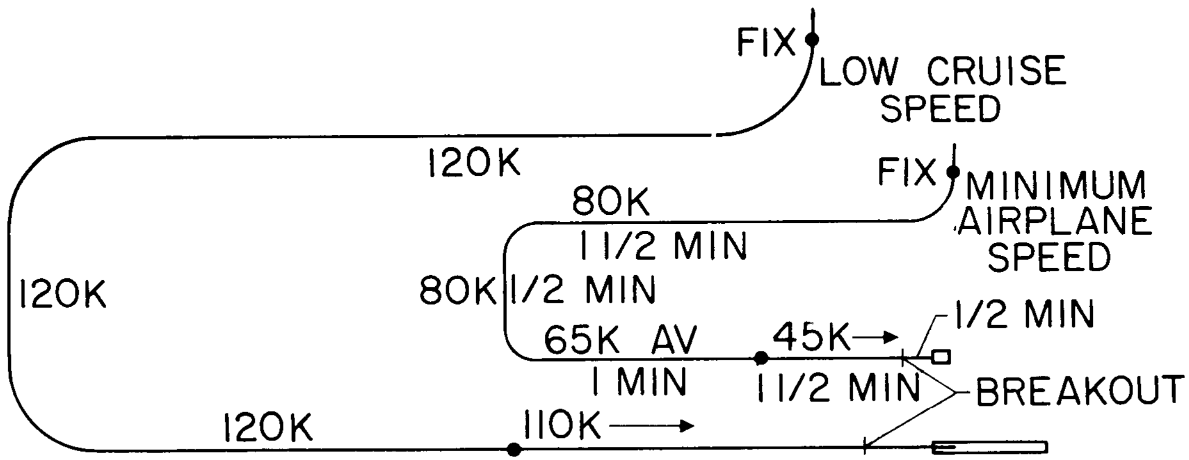
Figure 5.- "Sidestep" maneuvers calculated for 10° bank angle at two speeds. Time required is constant.



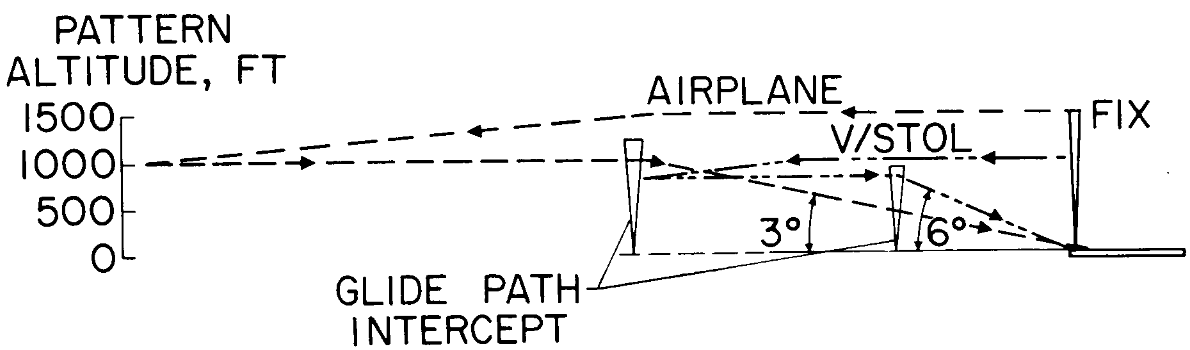


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Figure 6.- Comparison of instrument approach patterns for V/STOL and conventional aircraft.

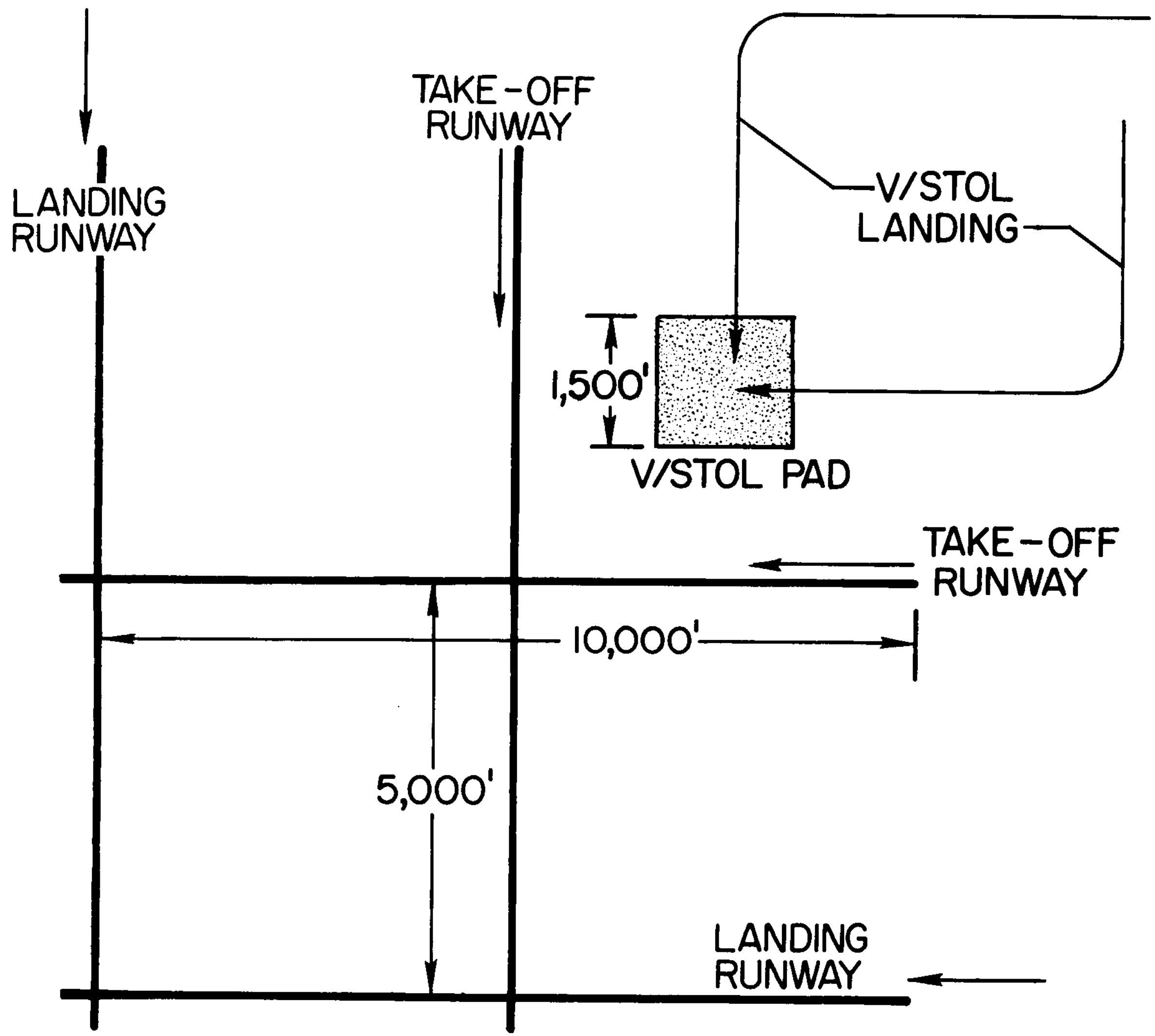

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Figure 7.- Possible airport layout to accommodate mixed V/STOL-CTOL traffic.

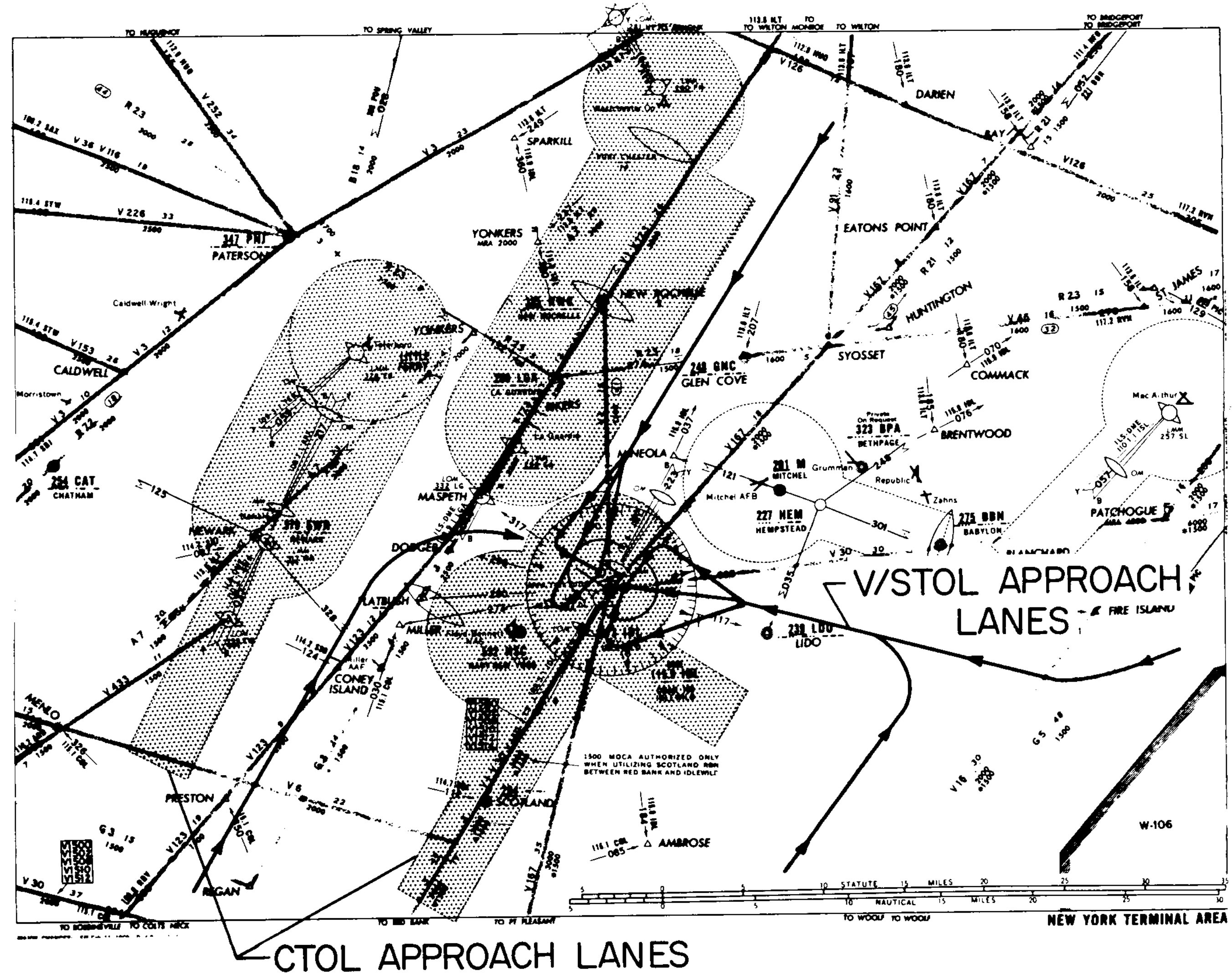

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Figure 8.- Possible lower level routings into V/STOL approach facilities at a major airport.

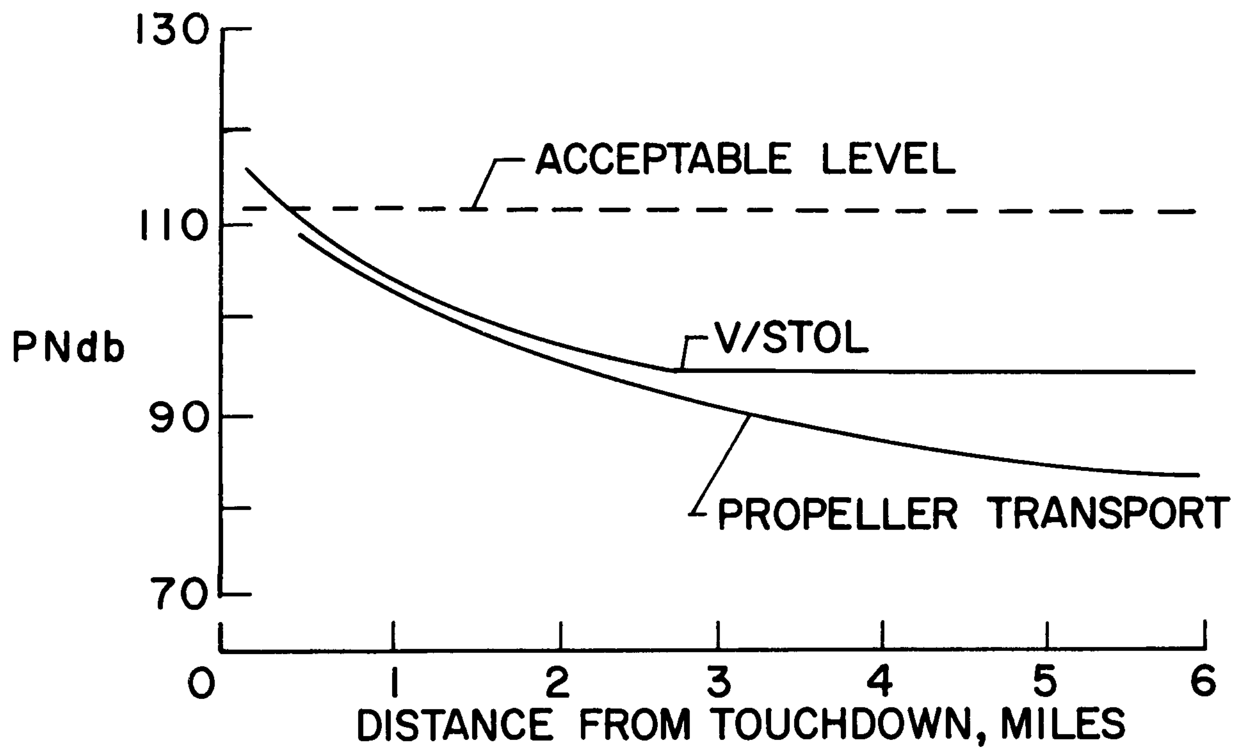

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Figure 9.- Landing noise for propeller V/STOL of about 55,000 pounds and transport airplane. The V/STOL is descending at 6°.

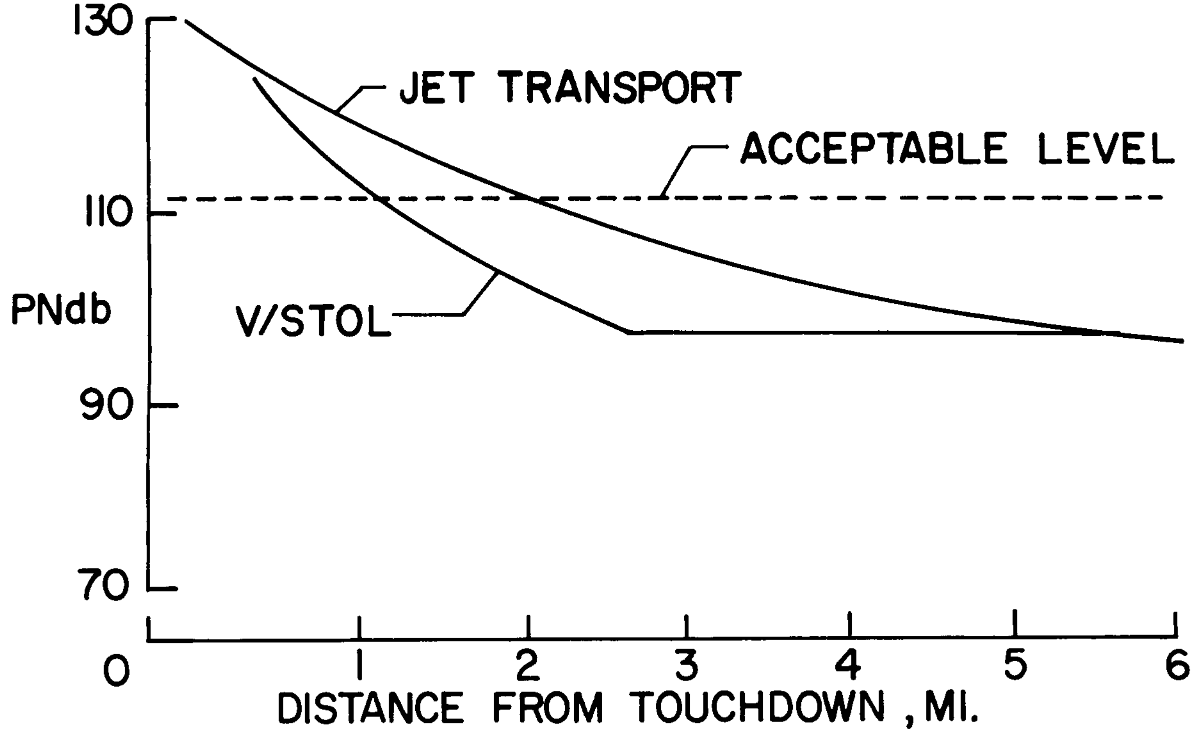

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Figure 10.- Landing noise for jet V/STOL of about 70,000 pounds and transport airplanes. The V/STOL is descending at 6°.

NASA-Langley, 1964